Aggregate-Associated Carbon and Nitrogen Affected by Residue Placement, Crop Species, and Nitrogen Fertilization

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Abstract: High variability in soil and climatic conditions results in limited changes in soil aggregate–associated carbon (C) and nitrogen (N) levels as affected by management practices during a crop-growing season in the field. We evaluated the effects of crop species (spring wheat [*Triticum aestivum* L.], pea [*Pisum sativum* L.], and fallow), N fertilization rate (0.11 and 0.96 g N pot^{-1}), and residue placement (no residue, surface placement, and incorporation into the soil) and rate (0, 20, and 40 g pot^{-1}) on soil aggregation and C and N contents during a growing season under controlled soil and climatic conditions in the greenhouse. Soil samples collected from the field were grown with crops in the greenhouse and analyzed for aggregation and soil organic C, total N, particulate organic C, and particulate organic N contents in aggregates. Residue C and N losses, proportion of macroaggregates (>0.25 mm), and soil C and N contents in microaggregates (<0.25 mm) were higher in surface residue placement (20 g pot^{-1}) under pea with 0.11 g N pot^{-1} than the other treatments. The soil organic C and soil total N were greater in surface residue placement (40 g pot^{-1}) under wheat with 0.96 g N pot^{-1} in large and intermediate macroaggregates (8.00–4.75 and 4.75–2.00 mm, respectively), particulate organic N was greater in surface residue placement (20 g pot^{-1}) under pea with 0.11 g N pot in large macroaggregates, but particulate organic C was greater in residue incorporation (20 g pot^{-1}) under fallow with 0.96 g N pot^{-1} in intermediate macroaggregate than the other treatments. Under controlled soil and environmental conditions, soil C and N levels in aggregates changed rapidly during a crop-growing season. Surface residue placement increased soil aggregation and C and N storage with concurrent losses of residue C and N, but residue incorporation increased coarse organic matter fraction. Results from this short-term experiment in the greenhouse agree with those obtained from the long-term study in the field.

Key Words: Soil aggregation, carbon fractions, nitrogen fractions, management practices

(*Soil Sci* 2014;179: 153–165)

Carbon (C) and nitrogen (N) sequestration as a result of crop residue returned to the soil or through amendment application primarily occurs in aggregates because soil is composed of various aggregate size classes (Mendes et al., 1999; Six et al., 1998, 2000; Wright and Hons, 2005). Mineralization of soil organic C (SOC) and total N (STN) is often prevented within aggregates, which reduce microbial access to the organic substrates (Elliott, 1986; Six et al., 2000). Formation and turnover rate of aggregates affect retention of C and N in macroaggregates (>0.25 mm) (Six et al., 1998). Carbon and N from recent crop residues are first incorporated into macroaggregates, which upon degradation, form the core of new microaggregates (Jastrow et al., 1996; Six et al., 1998; Gale et al., 2000). Therefore, management practices that promote soil aggregation and enrich C and N levels are needed to increase C and N sequestration, reduce soil erosion, C and N losses, and greenhouse gas emission and improve soil quality and productivity.

Residue placement at the soil surface due to the no-till practice can increase soil aggregation and C and N sequestration (Six et al., 1998; Wright and Hons, 2005). Tillage can disrupt aggregation and mineralize SOC and STN by disturbing soil, incorporating plant residues, increasing aeration, and affecting microbial communities (Beare et al., 1994; Paustian et al, 1997). Macroaggregates are more disrupted by tillage than microaggregates (<0.25 mm), making SOC and STN in macroaggregates more susceptible to mineralization (Cambardella and Elliott, 1993; Six et al., 2000). Similarly, crop species can influence soil aggregation and organic matter level by the quality and quantity of crop residue returned to the soil (Wright and Hons, 2005). Roots have a dominant effect on soil aggregation and C and N cycles than shoots, which primarily supply nutrients to succeeding crops (Gale and Cambardella, 2000; Puget and Drinkwater, 2001). Residue quality, such as C/N ratio, alters the rate of decomposition of the residues and therefore soil aggregation (Chesire and Chapman, 1996; Sainju et al., 2003). Similarly, N fertilization can affect soil aggregation and C and N levels by increasing the amount of crop residue returned to the soil (Whalen and Chang, 2002; Sainju et al., 2003).

Due to large background contents and inherent spatial variability, SOC and STN are often regarded as slow fractions of soil C and N because they change slowly over time as a result of management practices (Franzluebbers et al., 1995; Franzluebbers and Arshad, 1997). In contrast, particulate organic C and N (POC and PON, respectively), which represent coarse organic matter fraction, have been considered as active fractions that change rapidly during a crop-growing season, provide substrates for microbes, and influence aggregation (Beare et al., 1994; Six et al., 1998; Gale et al., 2000). The distribution of SOC, STN, POC, and PON among soil aggregates is heterogeneous (Mendes et al., 1999; Gale et al., 2000; Sainju, 2006, Sainju et al., 2008). Whereas some have reported greater SOC and STN in macroaggregates (Seech and Beauchamp, 1988; Miller and Dick, 1995), others have reported greater POC and PON in intermediate size (0.25–1.00 mm) aggregates (Six et al., 1998; Gale et al., 2000; Sainju, 2006, Sainju et al., 2008). The differences in C and N fractions among aggregate-size classes result from soil properties, such as clay and organic matter contents and clay mineralogy (Franzluebbers and Arshad, 1997; Six et al., 2000).

Because of high variability in soil and climatic conditions, changes in soil aggregate–associated C and N levels may not be readily obtained in the field (Franzluebbers et al., 1995; Franzluebbers and Arshad, 1997; Six et al., 2000). We hypothesized that the surface placement of residue under spring wheat with 96 g N pot^{-1} may increase soil aggregation and associated C and N levels compared with other treatments during a crop-growing season under

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Financial Disclosures/Conflicts of Interest: *None reported.*
Funding for this project was provided by USDA-ARS, Sidney, MT, and the National Natural Science Foundation of China (no. 31270484).
Received December 5, 2013.
Accepted for publication April 23, 2014.

ISSN: 0038-075X
DOI: 10.1097/SS.0000000000000051

controlled soil and environmental conditions in the greenhouse. Our objectives were to (1) evaluate the effects of residue placement and rate, crop species, and N fertilization rate on soil aggregation and associated SOC, STN, POC, and PON contents under controlled soil and climatic conditions in the greenhouse and (2) identify management practice that promote soil aggregation and C and N storage.

MATERIALS ANS METHODS

Experimental Description

The experiment was conducted under controlled soil and environmental conditions in the greenhouse with air temperatures of 25°C in the day and 15°C in the night. Soil samples were collected manually from an area of 5 m^2 using a shovel to a depth of 15 cm under a mixture of crested wheatgrass [*Agropyron cristatum* (L.) Gaertn] and western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Love] from a dryland farm site, 11 km east of Sidney, MT. The site was under spring wheat-fallow for 25 years, after which it was converted into grassland for 10 years when soil samples were collected. The soil was a Williams loam (fine-loamy, mixed, frigid, Typic Argiborolls [International classification: Luvisols]) with 350 g kg^{-1} sand, 325 g kg^{-1} silt, 325 g kg^{-1} clay, 1.42 Mg m^{-3} bulk density, and 7.2 pH at the 0- to 15-cm depth at the time of sampling. At the same time, SOC and STN contents in the sample were 94.4 g C pot^{-1} and 10.3 g N pot^{-1}, respectively. Soil was air dried and sieved to 4.75 mm after discarding coarse organic materials and rock fragments. Eight kilograms of soil was placed in a plastic pot, 25-cm height by 25-cm diameter, above 3 cm of gravel at the bottom to improve drainage, and leaving 1 cm above soil surface for water application. The volume of the soil in the pot was 0.01 m^3.

Treatments consisted of 12 incomplete combinations of residue placement (surface placement vs. incorporation into the soil) and rate (0, 20, and 40 g pot^{-1}), crop species (spring wheat, pea, and fallow), and N fertilization rates (0.11 and 0.96 g N pot^{-1}) (Treatments T1 to T12) (Table 1). In order to match the residue and crop species, spring wheat residue was placed under spring wheat and pea residue under pea. Spring wheat residue was also placed under the fallow. Residues included 9-week-old spring wheat and pea plants collected from the field without grains, chopped to 2 cm, mixed within a species, and oven dried at 60°C for 3 days. Residues were either placed at the soil surface for the surface placement treatment or incorporated into the soil by mixing the residue with the soil by hand for the incorporated treatment. The surface placement of residue corresponded to the simulated no-till system, although the soil was disturbed during collection, and incorporated residue to the conventional till system. Treatment T1 was the control treatment without any residue and plant. Residue rate of 20 g pot^{-1} (2.5 g kg^{-1} soil or 3,550 kg ha^{-1}) was the normal amount of residue found under dryland spring wheat and pea at the experimental site. The 0.96 g N pot^{-1} was similar to the recommended N fertilization rate (68 kg N ha^{-1}) to spring wheat in the field, whereas 0.11 g N pot^{-1} (or 8 kg N ha^{-1}) was applied from monoammonium phosphate, which was used as a P fertilizer. Half of 0.96 g N pot^{-1} was applied at planting, and the other half, both applied as urea, at 4 weeks later. To eliminate the variability due to N fertilization, fallow treatments were also applied with 0.11 g N pot^{-1}. All treatments were applied with P fertilizer (monoammonium phosphate) at 0.25 g P pot^{-1} (or 27 kg P ha^{-1}) and K fertilizer (muriate of potash) at 0.50 g K pot^{-1} (or 29 kg K ha^{-1}). Treatments were arranged in a completely randomized design with three replications.

TABLE 1. Description of Treatments Used in the Experiment

Treatment	Residue Placement	Residue Rate	Crop Species	N Fertilization
		g pot^{-1}		g N pot^{-1}
T1	No residue	0	Fallow	0.11
T2	Surface	20	Wheat	0.11
T3	Surface	20	Wheat	0.96
T4	Surface	20	Pea	0.11
T5	Surface	20	Fallow	0.11
T6	Surface	20	Fallow	0.96
T7	Surface	40	Wheat	0.96
T8	Incorporated	20	Wheat	0.11
T9	Incorporated	20	Wheat	0.96
T10	Incorporated	20	Pea	0.11
T11	Incorporated	20	Fallow	0.11
T12	Incorporated	20	Fallow	0.96

Wheat residue was applied under wheat and fallow and pea residue under pea.

In July 2012, five spring wheat and pea seeds were planted per pot, except in the fallow treatment. At a height of 3 cm, seedlings were thinned to two per pot. Water was applied in all treatments to field capacity (0.25 m^3 m^{-3}) (Pikul and Aase, 2003) at 300 to 500 mL pot^{-1} at planting and at 3- to 7-day intervals thereafter, depending on soil water content. The soil water content was determined by using a TDR 300 soil moisture meter with a range of 0% to 50% volumetric water content (Spectrum Technologies Inc., Aurora, IL) installed to a depth of 15 cm. Because the amount of applied water was based on soil water content in the pot, only a negligible amount of water was lost from the bottom of the pot, which was not measured. At 105 days after planting, shoot biomass was harvested from the pot, washed with water, and oven dried at 60°C for 3 to 7 days, and dry matter yield was determined. Because of the small amount of grain production due to reduced root growth in limited soil volume in the plot, grains were also included in the shoot biomass. After crop harvest, undecomposed crop residue (>2 mm) left in the soil as revealed by the naked eye (different from live roots) was removed by hand and/or tweezers, washed with water, and oven dried at 60°C for 3 to 7 days, and dry matter yield determined. After mixing the soil from each pot gently so as not to destroy soil aggregates, a portion (200 g) of residue and root-free soil sample (after removing coarse and fine roots as detected by the naked eye) was sieved to 8 mm and stored at 4°C for determination of soil aggregation and C and N fractions. The remaining soil samples were washed in a nest of 1.0- and 0.5-mm sieves under a continuous stream of water to separate roots. Roots left in sieves were picked using tweezers and oven dried at 60°C for 3 to7 days, and dry matter yield was determined.

Carbon and N concentrations in shoot and root biomass and crop residues added to the soil at the initiation of the experiment and those (>2.00 mm) recovered from the soil at the end were determined with a high induction furnace C and N analyzer (LECO, St. Joseph, MI) after grinding samples to 1 mm. Amounts of C and N in the residue added and recovered from the soil were determined by multiplying C and N concentrations by the weight of the soil in the pot. Carbon and N losses from the residue were determined as follows: residue C or N loss (g pot^{-1}) = (residue C or N added − residue C or N recovered) and residue C or N loss (%) = (residue C or N added − residue C or N recovered) × 100 / residue C or N added. While determining the amount of C and

N recovered in the residue, it was assumed that fine residue (<2.00 mm) was a part of soil organic matter.

Aggregate Separation

Aggregates were separated by using the dry sieving method as shown by Mendes et al. (1999) and Schutter and Dick (2002). Moist soils were air dried at 4°C for 7 to 10 days until they reached a gravimetric water content of 80 to 100 g kg^{-1}. This water content represented the moisture level at which soils can be sieved in finer sieves for aggregate size separation according to our preliminary observations (data not shown). Microbial communities and activity were less impacted by drying the soil at 4°C (Mendes et al., 1999; Schutter and Dick, 2002). Aggregates were separated by placing 200 g of soil fragments (≤8.00 mm) in a nest of sieves containing 4.75−, 2.00−, and 0.25-mm sieves attached to a Tyler Ro-Tap sieve shaker (Combustion Engineering Inc., Mentor, OH). Sieves were shaken at 200 oscillation min^{-1} for 3 min, and aggregates retained and passed through the sieves were weighed (Mendes et al., 1999; Schutter and Dick, 2002). Aggregates retained on the 4.75-mm sieve were denoted as large macroaggregates (8.00–4.75 mm), on the 2.00-mm sieve as intermediate macroaggregates (4.75–2.00 mm), and on the 0.25-mm sieve as small macroaggregates (2.00–0.25 mm). Aggregates that passed through the 0.25-mm sieve were denoted as microaggregates and silt and clay fractions (<0.25 mm). Aggregates were air dried at room temperature and stored in plastic bags until C and N fractions were determined.

For determining the proportion of water-stable aggregates, large macroaggregates were further sieved by using the capillary-wetted wet sieving method (Gale et al., 2000). Five grams of aggregates was placed in a filter paper (150-mm diameter) in a Petri dish and capillary wetted to 280 g H_2O kg^{-1} soil by slowly adding water to the edges of the filter paper. Aggregates were allowed to absorb water by placing the sample in the refrigerator at 4°C overnight. Aggregates were separated by submerging samples in water in a 4.75-mm sieve for 3 cm vertically with 50 repetitions for 2 min. Aggregates retained in the sieve (8.00–4.75 mm) were air dried at room temperature, weighed, and stored in a plastic bag. Sieving was repeated as above using the next sieve (2.00 mm) by pouring the soil and water that passed through the 4.75-mm sieve in the 2.00-mm sieve and shaking. Aggregates retained in the sieve (4.75–2.00 mm) were collected, air dried, weighed, and stored in a plastic bag. Those that passed through the 2.00-mm sieve were discarded. The amount of aggregates of various size classes in the pot was determined by multiplying aggregate proportion by the weight of the soil in the pot.

Soil Carbon and Nitrogen Analysis

The SOC and STN concentrations (g C or N kg^{-1} aggregate) in air-dried aggregates were determined with a high-induction furnace C and N analyzer as above after grinding a portion of the aggregate to 0.5 mm. Because pH was close to 7.0, soil total C was considered as SOC (Nelson and Sommers, 1996). Previous observations have shown that C concentrations in soil samples with or without the acid treatment (5% H_2SO_3) to remove inorganic C (Nelson and Sommers, 1996) in the top 15-cm soil were similar and that the presence of inorganic C was negligible (data not shown). For determining POC and PON, 5 g aggregates were dispersed with 15 mL of 5 g L^{-1} sodium hexametaphosphate by shaking for 16 h, and the solution was poured through a 0.053-mm sieve (Cambardella and Elliott, 1993). The solution and particles that passed through the sieve and contained mineral-associated and water-soluble C were dried at 50°C for 3 to 4 days, and SOC and STN concentrations were determined by using the analyzer as above. The POC and PON concentrations were determined by the difference between SOC and STN in the aggregates and those in the particles that passed through the sieve after correcting for the sand content. Because significant amounts of C and N can be lost through wet sieving compared with dry sieving (Sainju 2006), it was decided to determine C and N concentrations in aggregates separated by dry sieving rather than wet sieving. Carbon and N contents in aggregates in the pot were determined by multiplying aggregate amount by C and N concentrations.

Data Analysis

Data for C and N contents in crop biomass and residue, aggregate proportion, and soil C and N fractions were analyzed by using the MIXED model of SAS (Littell et al., 1996). Treatment was considered as the main plot and fixed effect, aggregate size class as the split plot and another fixed effect, and replication and treatment × replication as random effects. Because the experiment contained incomplete combinations of individual treatments (crop species, N fertilization rate, and residue placement), data containing similar levels of individual treatments were further analyzed to evaluate the interactive effects of the treatments on response variables. For example, for evaluating the interactive effects of residue placement, crop species (spring wheat and fallow), and N fertilization at 20 g pot^{-1} residue rate, data for Treatments T2, T3, T5, T6, T8, T9, T11, and T12 were analyzed separately (Figs. 1–6). Similarly, for evaluating the interactive effects of residue placement and crop species (spring wheat, pea, and fallow) at 20 g pot^{-1} residue rate and 0.11 g N pot^{-1}, data for Treatments T2, T4, T5, T8, T10, and T11 were analyzed separately. Means were separated by using the least-squares means test when treatments and interactions were significant (Littell et al., 1996). When treatments were significant, orthogonal contrasts were used to determine the effects of residue presence (T5 + T11 vs. T1) and rate (T7 vs. T3) on soil C and N fractions (Littell et al., 1991). Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

RESULTS AND DISCUSSION

Crop Residue Carbon and Nitrogen Losses

The amounts of C and N added to the soil through residue placement and leaf fall during crop growth were higher in surface placement of residue (40 g pot^{-1}) under spring wheat with 0.96 g N pot^{-1} (Treatment T7) than the other treatments (Table 2) because of higher residue rate (Table 1). Although treatments with identical crop species and residue rates (e.g., Treatments T2, T3, T5, T6, T7, T8, T9, T11, and T12) added similar levels of residue C and N, the level varied among treatments because of the small amount of residue added through leaf fall. Higher N concentration in pea residue than spring wheat residue also increased residue N addition in surface placement of residue under wheat with 0.11 g N pot^{-1} (T4) and residue incorporation under pea with 0.11 g N pot^{-1} (T10).

The amount of C recovered in coarse residue (>2 mm) after crop harvest was greater in T7 than the other treatments, a result of greater residue rate (Table 2). Carbon recovery was also greater in surface residue placement under fallow with 0.11 g N pot^{-1} (T5) than surface residue placement under pea with 0.11 g N pot^{-1} (T4) and incorporated residue under fallow with 0.96 g N pot^{-1} (T12). In contrast, N recovery was greater in surface residue placement under spring wheat with 0.96 g N pot^{-1} (T3) than the other treatments, except in no residue or surface placement of residue under wheat and fallow with 0.11 to 0.96 g N pot^{-1} (T1, T2, T5, and T6). While increased residue rate may have increased C

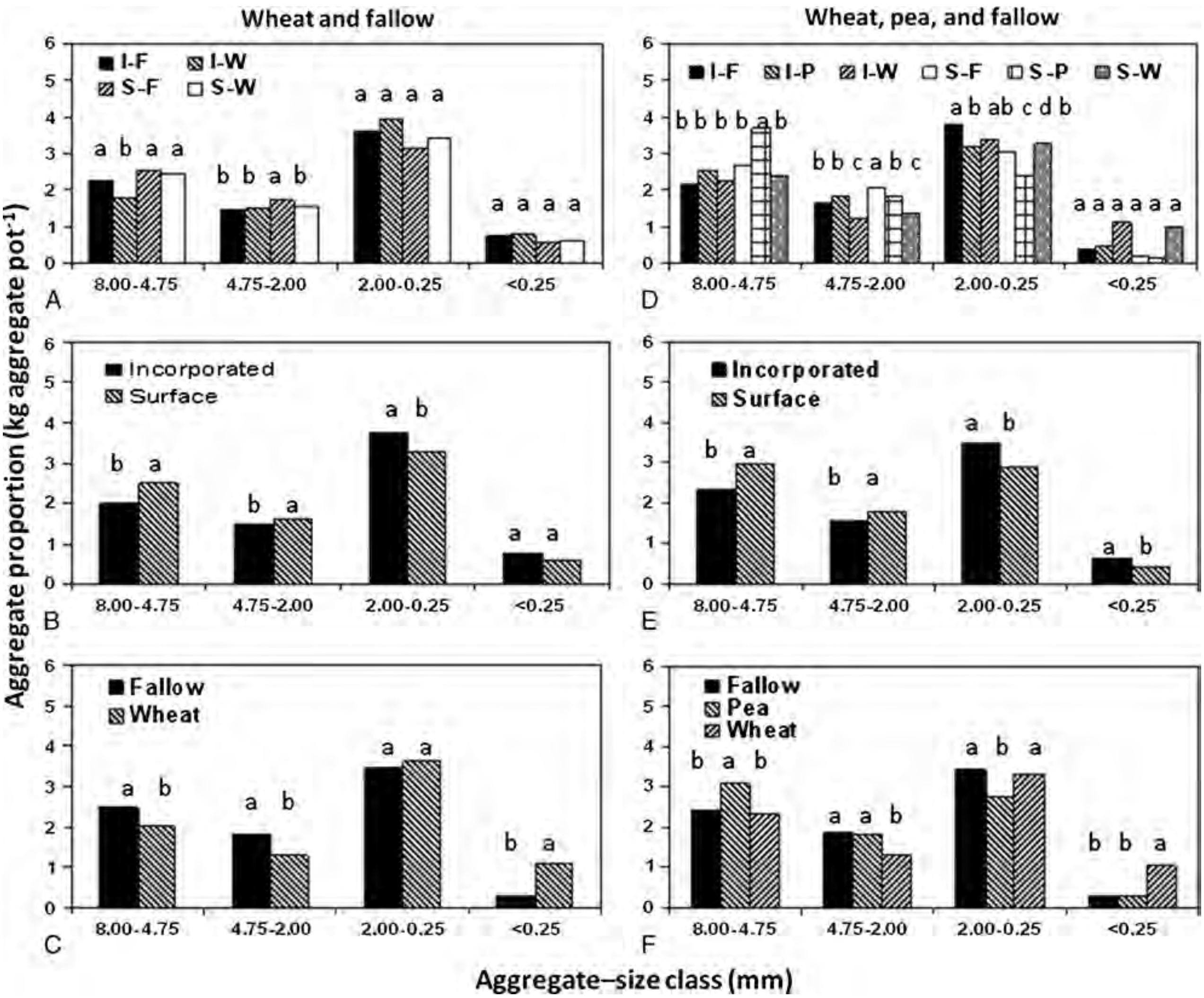

FIG. 1. Effects of residue placement and crop species on soil aggregate proportion under spring wheat and fallow (A, B, and C) and under spring wheat, pea, and fallow (D, E, and F). The values were obtained by using multiple comparison tests of treatments T2, T3, T5, T6, T8, T9, T11, and T12 for spring wheat and fallow and treatments T2, T4, T5, T8, T10, and T11 for spring wheat, pea, and fallow. Letters in the legend denote F, fallow; I, incorporated residue; P, pea; S, surface residue; and W, spring wheat. Bars followed by different letters at the top are significantly different at $P \leq 0.05$ by the least-squares means test.

recovery in T7, surface placement probably decreased residue C and N mineralization because of reduced contact of the residue with soil microorganisms, thereby increasing C and N recovery in T3 and T5 (surface residue placement under fallow with 0.11 g N pot^{-1}). Residue incorporated into the soil is mineralized rapidly because of increased contact with soil microorganisms compared with residue placed at the soil surface (Coppens et al., 2006; Giacomini et al., 2007). Lower C/N ratio of pea residue than spring wheat residue may have increased C and N mineralization and therefore reduced C and N recovery in surface residue placement under pea with 0.11 g N pot^{-1} (T4). Residues of legumes, such as pea with lower C/N ratio, decompose more rapidly than those of nonlegumes, such as wheat with higher ratio (Kuo et al., 1997). This may have resulted in greater residue C and N losses in T4 than the other treatments, except for the C loss in residue incorporation under fallow with 0.96 g N pot^{-1} (T12) (Table 2). In T12, increased microbial activity due to higher soil temperature and fallow during fallow (Halvorson et al., 2002) and greater N substrate availability due to higher N fertilization rate may have increased C mineralization, thereby resulting in increased C loss. Increased C and N losses from the residue may have translated into increased soil aggregation and associated C and N levels, as described in the following section.

Soil Aggregation

Aggregate proportion was greater in surface residue placement under pea with 0.11 g N pot^{-1} (T4) in the 8.00- to 4.75-mm size class and surface residue placement under fallow with 0.11 g N pot^{-1} (T5) in the 4.75- to 2.00-mm size class than most other treatments (Table 3). In the size class 2.00 to 0.25 mm, aggregate proportion was greater in residue incorporation under wheat with 0.96 g N pot^{-1} (T9) than no residue or surface residue placement and residue incorporation under pea and fallow with 0.11 to 0.96 g N pot^{-1} (T1, T4, T5, T6, and T10). In the size class of less than 0.25 mm, aggregate proportion was greater in surface residue placement under wheat with 0.96 g N pot^{-1} (T7) than no residue or surface residue placement and residue incorporation under pea and fallow with 0.11 to 0.96 g N pot^{-1} (T1, T4, T5,

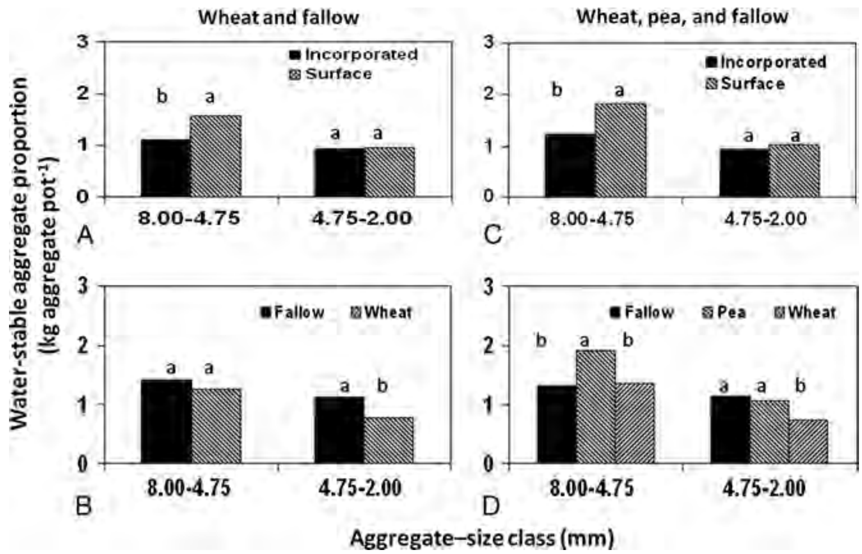

FIG. 2. Effects of residue placement and crop species on soil water-stable aggregate proportion under spring wheat and fallow (A and B) and under spring wheat, pea, and fallow (C and D). The values were obtained by using multiple comparison tests of treatments T2, T3, T5, T6, T8, T9, T11, and T12 for spring wheat and fallow and treatments T2, T4, T5, T8, T10, and T11 for spring wheat, pea, and fallow. Bars followed by different letters at the top are significantly different at $P \leq 0.05$ by the least-squares means test.

T6, T9, T10, T11, and T12). Aggregate proportion, averaged across treatments, was greater in the 2.00- to 0.25-mm size class than the other size classes. When pea was excluded in the data analysis of crop species effects on soil aggregation, aggregate proportion, averaged across N fertilization rates, was lower in residue incorporation under spring wheat in the 8.00- to 4.75-mm size class, but was greater in surface residue placement under fallow in the 4.75- to 2.00-mm size class than the other treatments (Fig. 1).

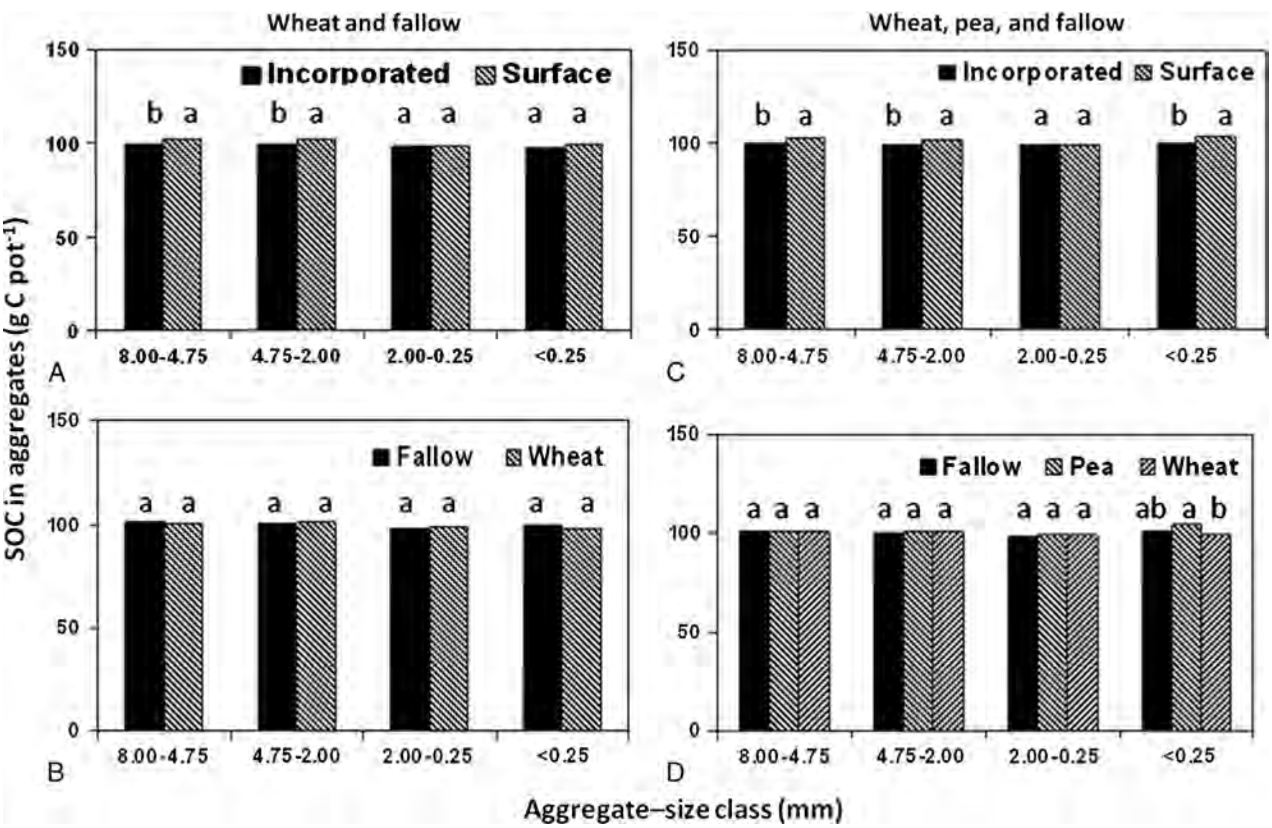

FIG. 3. Effects of residue placement and crop species on soil organic C (SOC) in aggregates under spring wheat and fallow (A and B) and under spring wheat, pea, and fallow (C and D). The values were obtained by using multiple comparison tests of treatments T2, T3, T5, T6, T8, T9, T11, and T12 for spring wheat and fallow and treatments T2, T4, T5, T8, T10, and T11 for spring wheat, pea, and fallow. Bars followed by different letters at the top are significantly different at $P \leq 0.05$ by the least-squares means test.

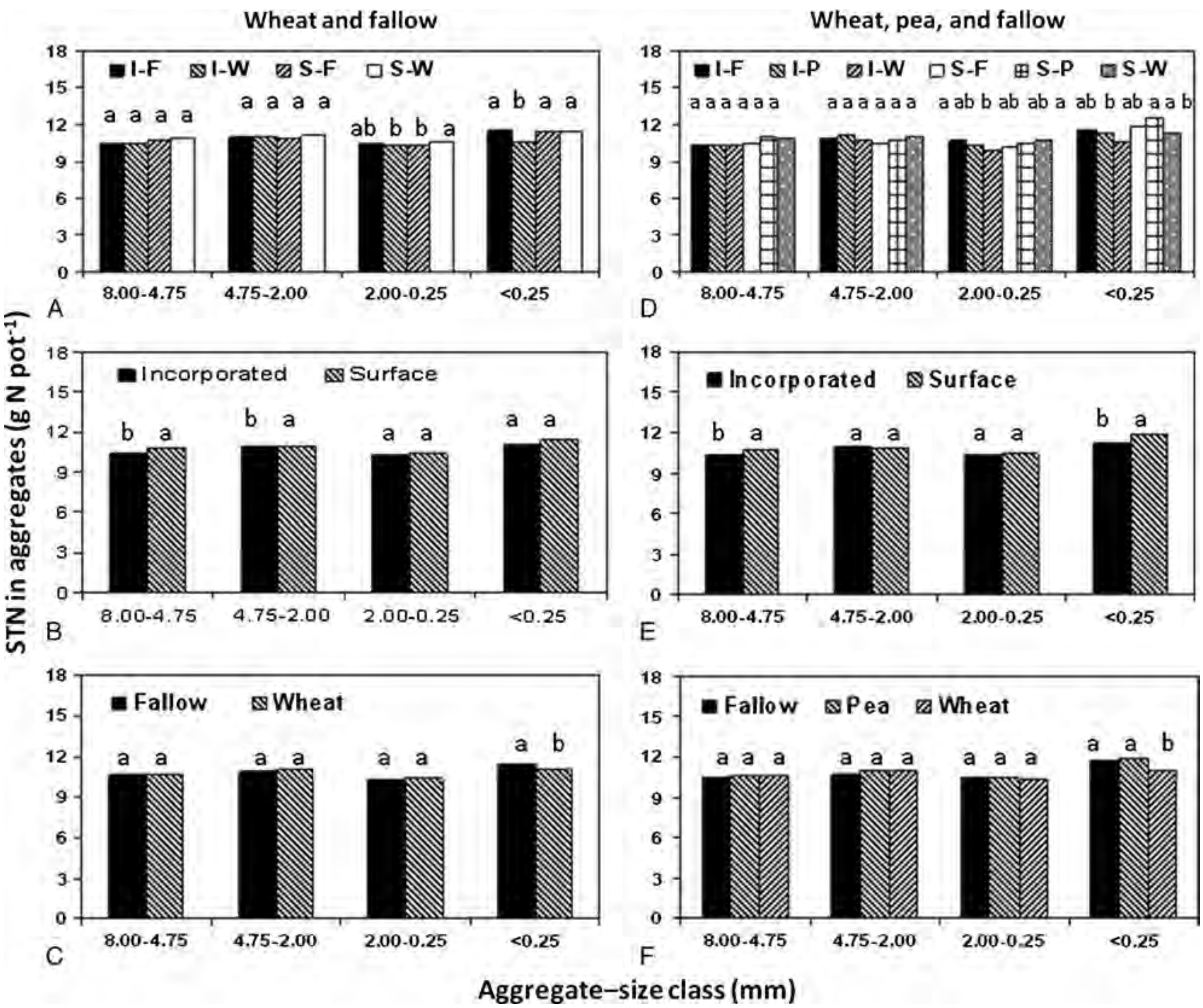

FIG. 4. Effects of residue placement and crop species on soil total N (STN) in aggregates under spring wheat and fallow (A, B, and C) and under spring wheat, pea, and fallow (D, E, and F). The values were obtained by using multiple comparison tests of treatments T2, T3, T5, T6, T8, T9, T11, and T12 for spring wheat and fallow and treatments T2, T4, T5, T8, T10, and T11 for spring wheat, pea, and fallow. Letters in the legend denote F, fallow; I, incorporated residue; P, pea; S, surface residue; and W, spring wheat. Bars followed by different letters at the top are significantly different at $P \leq 0.05$ by the least-squares means test.

Aggregate proportion, averaged across crop species and N rates, was greater in surface residue placement than residue incorporation in the 8.00- to 4.75-mm and 4.75- to 2.00-mm size classes, but the trend reversed in the 2.00- to 0.25-mm size class. Averaged across residue placements and N rates, aggregate proportion was greater under fallow than spring wheat in the 8.00- to 4.75-mm and 4.75- to 2.00-mm size classes, with a subsequent reverse trend in the <0.25-mm size class. When pea was included, aggregate proportion was greater in surface residue placement under pea in the 8.00- to 4.75-mm size class and under fallow in the 4.75- to 2.00-mm size class, but greater in residue incorporation under fallow in the 2.00- to 0.75-mm size class than the other treatments. Averaged across crop species, aggregate proportion was greater in surface residue placement than residue incorporation in the 8.00- to 4.75-mm and 4.75- to 2.00-mm size classes, but the trend reversed in the 2.00- to 0.25-mm and <0.25-mm size classes. Averaged across residue placements, aggregate proportion was greater under fallow or pea than spring wheat in the 8.00- to 4.75-mm and 4.75- to 2.00-mm size classes, but greater under spring wheat or fallow than pea in the 2.00- to 0.25-mm and <0.25-mm size classes. Nitrogen fertilization and residue rate had no effect on soil aggregation, but residue presence in the fallow increased aggregate proportion in the 4.75- to 2.00-mm and 2.00- to 0.25-mm size classes.

Increased soil water content due to fallow or reduced water uptake by pea compared with spring wheat and surface residue placement probably increased proportions of large and intermediate macroaggregates (8.00- to 4.75-mm and 4.75- to 2.00-mm size classes, respectively) in T4 and T5. While surface residue placement, acting like mulch, can conserve soil water better than residue incorporation, absence of crops during fallow can increase soil water content (Halvorson et al., 2002; Lenssen et al., 2010). Pea uses less water than spring wheat, thereby increasing soil water content (Miller et al., 2002; Lenssen et al., 2010). Increased soil water content can increase the proportion of macroaggregates by attracting soil particles together and forming large aggregates (Kemper and Resenau, 1986). Another possibility would be the rapid decomposition of pea residue due to its lower

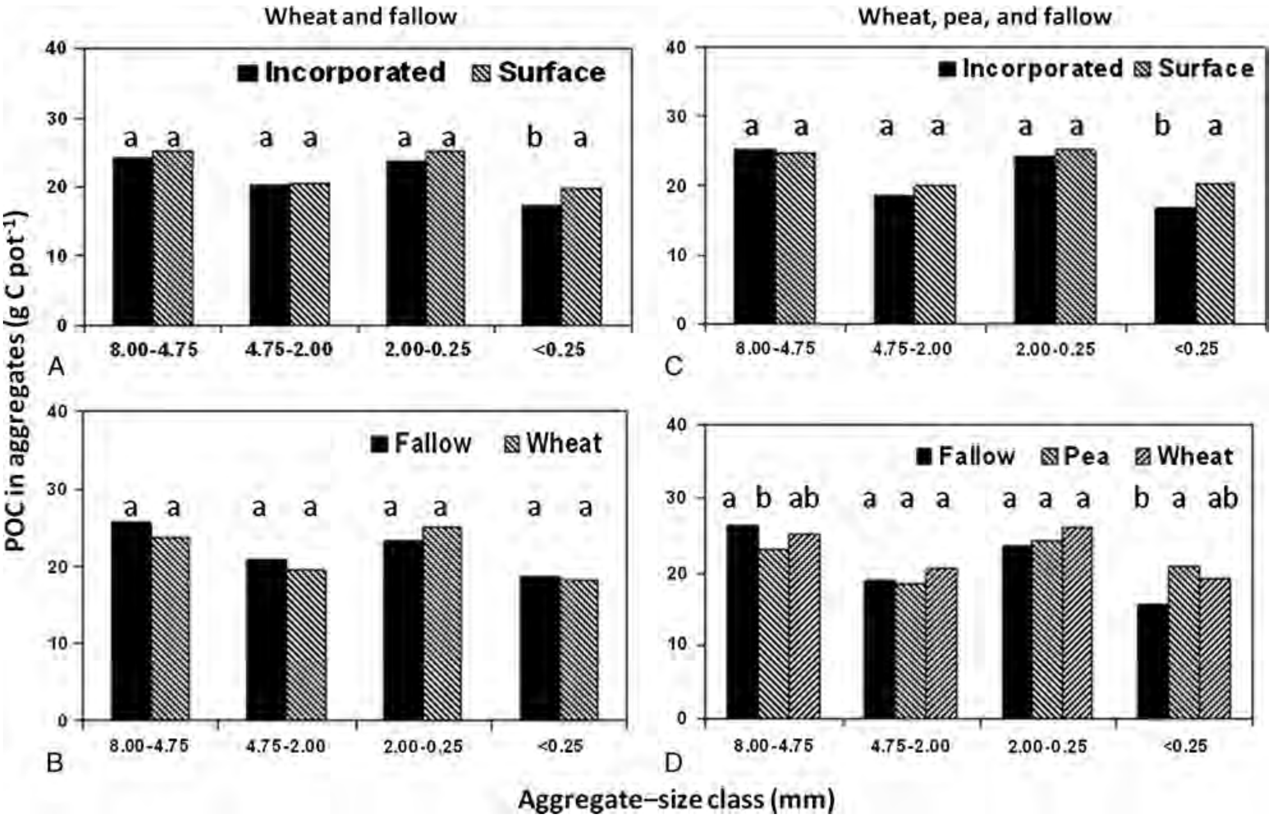

FIG. 5. Effects of residue placement and crop species on soil particulate organic C (POC) in aggregates under spring wheat and fallow (A and B) and under spring wheat, pea, and fallow (C and D). The values were obtained by using multiple comparison tests of treatments T2, T3, T5, T6, T8, T9, T11, and T12 for spring wheat and fallow and treatments T2, T4, T5, T8, T10, and T11 for spring wheat, pea, and fallow. Bars followed by different letters at the top are significantly different at $P \leq 0.05$ by the least-squares means test.

C/N ratio than spring wheat residue (Kuo et al., 1997) or to greater residue mineralization due to increased microbial activity as a result of increased soil temperature and water content in the fallow (Halvorson et al., 2002) as shown by increased residue C and N losses in T4 (Table 2). This may have increased the proportion of transient stable macroaggregates during a growing season (Sun et al., 1995). Gale et al. (2000) reported that proportion of macroaggregates increased with increased duration of soil incubation, followed by a rapid loss of residue C. Such increased proportion of macroaggregates in the 2.00- to 0.25-mm size class in no till than conventional till and in crop-fallow than continuous cropping after 21 years of tillage and cropping sequence in the field was also noted by Sainju et al. (2009). With subsequent decreases in the proportions of large and intermediate macroaggregates, proportion of small macroaggregates (2.00–0.25 mm) and microaggregates and silt and clay fractions (<0.25 mm) may have increased in T7 and T9. These results were further substantiated by greater proportions of large and intermediate macroaggregates in surface residue placement than residue incorporation or greater under fallow or pea than under spring wheat (Fig. 1). Incorporation of residue into the soil may have reduced the proportions of large and intermediate macroaggregates by increasing residue mineralization and reducing the levels of POC and PON that binds the aggregates, as shown below. Greater proportion of aggregates in the intermediate (2.00–0.25 mm) than the large or small size classes have also been reported by various researchers (Schutter and Dick, 2002; Sainju, 2006, Sainju et al., 2009).

The proportion of water-stable aggregates was also greater in surface residue placement under pea with 0.11 g N pot^{-1} (T4) than the other treatments, except surface residue placement under wheat and fallow with 0.11 to 0.96 g N pot^{-1} (T2 and T6) in the 8.00- to 4.75-mm size class (Table 3). In the 4.75- to 2.00-mm size class, the proportion was greater in surface residue placement under fallow with 0.11 g N pot^{-1} (T5) than the other treatments, except surface placement or incorporation of residue under wheat and pea with 0.11 to 96 g N pot^{-1} (T4, T6, T10, T11, and T12). With the exclusion of pea in crop species, aggregate proportion, averaged across crop species and N rates, was greater in surface residue placement than residue incorporation in the 8.00- to 4.75-mm size class (Fig. 2). Averaged across residue placements and N rates, aggregate proportion was greater under fallow than spring wheat in the 4.00- to 2.75-mm size class. With the inclusion of pea, aggregate proportion, averaged across crop species, was also greater in surface residue placement than residue incorporation in the 8.00- to 4.75-mm size class. Averaged across residue placements, aggregate proportion was greater under pea than spring wheat and fallow in the 8.00- to 4.75-mm size class and greater under fallow and pea than spring wheat in the 4.75- to 2.00-mm size class. As with dry-sieved aggregates, N fertilization did not influence the proportion of water-stable aggregates, but residue presence in the fallow increased water-stable aggregates in the 4.75- to 2.00-mm size class. In contrast, aggregate proportion, averaged across treatments, was greater in the 8.00- to 4.75-mm than the 4.75- to 2.00-mm size class (Table 3). Increased soil water content appeared to increase both water-stable and unstable macroaggregates (wet- and dry-sieved

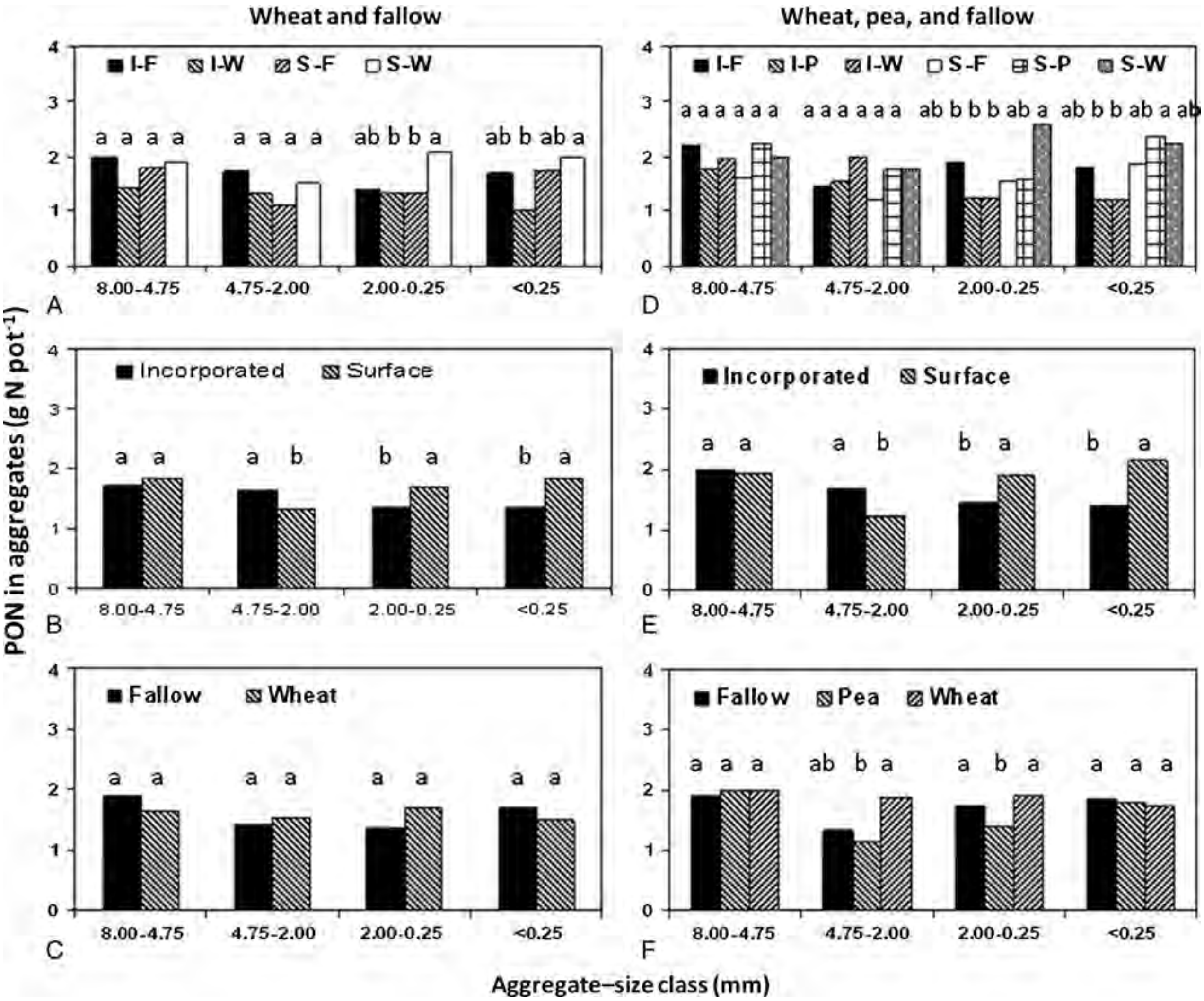

FIG. 6. Effects of residue placement and crop species on soil particulate organic N (PON) in aggregates under spring wheat and fallow (A, B, and C) and under spring wheat, pea, and fallow (D, E, and F). The values were obtained by using multiple comparison tests of treatments T2, T3, T5, T6, T8, T9, T11, and T12 for spring wheat and fallow and treatments T2, T4, T5, T8, T10, and T11 for spring wheat, pea, and fallow. Letters in the legend denote F, fallow; I, incorporated residue; P, pea; S, surface residue; and W, spring wheat. Bars followed by different letters at the top are significantly different at $P \leq 0.05$ by the least-squares means test.

aggregates, respectively) in treatments with surface residue placement under pea or fallow compared with other treatments. Increased substrate availability for soil microorganisms due to residue presence in the fallow also appeared to increase both water-stable and unstable macroaggregates, since soil organic matter acts as binding agent for aggregation (Elliott, 1986; Mendes et al., 1999). Presence of greater proportion of water-stable aggregates in the 8.00- to 4.75-mm size class suggests that most of large macroaggregates separated by dry sieving are water stable.

Soil Organic Carbon and Total Nitrogen

Soil organic C was greater in surface residue placement (40 g pot^{-1}) under wheat with 0.96 g N pot^{-1} (T7) than no residue or residue incorporation (20 g pot^{-1}) under wheat, pea, and fallow with 0.11 to 0.96 g N pot^{-1} (T1, T9, T10, and T12) in the 4.75- to 2.00-mm size class (Table 4). In the <0.25-mm size class, SOC was greater in surface residue placement under pea with 0.11 g N pot^{-1} (T4) than the other treatments, except surface residue placement under fallow with 0.11 g N pot^{-1} (T5). Averaged across treatments, SOC was greater in the 8.00- to 4.75-mm and 4.75- to 2.00-mm size classes than the other size classes. When pea was excluded in crop species for data analysis, SOC, averaged across crop species and N rates, was greater in surface residue placement than residue incorporation in the 8.00- to 4.75-mm and 4.75- to 2.00-mm size classes (Fig. 3). When pea was included, SOC, averaged across crop species, was greater in surface residue placement than residue incorporation in all size classes, except in the 2.00- to 0.25-mm size class. Averaged across residue placements, SOC was greater under pea than under spring wheat in the <0.25-mm size class. Nitrogen fertilization, presence of residue in the fallow, or residue rate had no effect on SOC in aggregates.

Surface placement of residue with higher rate (40 g pot^{-1}) under spring wheat probably increased SOC in intermediate macroaggregates in T7. While surface residue placement as a result of no-till can increase aggregate-associated SOC by reducing residue decomposition, residue quantity and quality can affect

TABLE 2. Effects of Residue Placement and Rate, Crop Species, and N Fertilization Rate on Residue C and N Losses During the Crop-Growing Period

	Crop Residue					
	C Added‡	N Added‡	C Recovered	N Recovered	C Loss§	N Loss§
Treatment†	g C pot^{-1}	g N pot^{-1}	g C pot^{-1}	g N pot^{-1}	g C pot^{-1}	g N pot^{-1}
T1	0	0	0	0	0 (0)	0 (0)
T2	8.92	0.46	4.95	0.31	3.97 (45)	0.15 (33)
T3	9.08	0.47	5.05	0.33	4.03 (44)	0.14 (30)
T4	7.80	0.64	3.82	0.23	3.98 (51)	0.41 (64)
T5	7.80	0.40	5.16	0.31	2.64 (34)	0.09 (21)
T6	7.80	0.40	4.89	0.28	2.91 (37)	0.12 (31)
T7	17.11	0.88	8.44	0.24	8.67 (51)	0.64 (45)
T8	8.60	0.44	4.89	0.24	3.71 (43)	0.20 (46)
T9	8.70	0.44	5.07	0.27	3.63 (42)	0.17 (40)
T10	7.80	0.64	4.24	0.26	3.56 (46)	0.38 (59)
T11	7.80	0.40	3.85	0.23	3.95 (50)	0.17 (44)
T12	7.80	0.40	3.81	0.23	3.99 (51)	0.17 (44)
LSD (0.05)	0.22	0.01	1.34	0.05	1.12	0.04
P	***	***	**	***	*	***

*Significant at $P = 0.05$.

**Significant at $P = 0.01$.

***Significant at $P = 0.001$.

†See Table 1 for treatment description.

‡Includes C and N added from the residue application and leaf fall.

§Residue C or N losses (g C or N pot^{-1}) = (residue C or N added − residue C or N recovered). Number in parenthesis denotes percentage of C or N loss.

SOC in aggregates in the field (Sainju et al., 2009). Both increased residue addition, and residue with higher C/N ratio can increase SOC in large aggregates because of reduced residue decomposition compared with reduced residue addition and residue with lower C/N ratio (Chesire and Chapman, 1996; Sainju et al., 2003; Wright and Hons, 2005). The opposite was true for increased SOC in microaggregates and silt and clay fractions in T4 due to increased mineralization of pea residue compared with wheat residue. Pea residue with lower C/N ratio than wheat residue may have decomposed rapidly (Kuo et al., 1997), resulting in rapid turnover of plant C into soil C in microaggregates and silt and clay fractions. It appeared that increased residue C loss from pea residue in T4 (Table 2) probably translated into increased SOC in the <0.25-mm aggregates. This was also supported by higher SOC under pea than under spring wheat in the <0.25-mm size class (Fig. 3). Increased SOC in macroaggregates was probably due to inclusion of microaggregates that contain C-rich young residues and binding agents (Angers et al., 1997, Six et al., 1998; Sainju et al., 2009).

Soil total N was greater in surface residue placement under fallow with 0.96 g N pot^{-1} (T6) than no residue or residue incorporation under wheat, pea, and fallow with 0.11 g N pot^{-1} (T1, T8, T10, and T11) in the 8.00- to 4.75-mm size class, but was greater in surface residue placement under pea with 0.11 g N pot^{-1} (T4) than the other treatments in the <0.25-mm size class (Table 4). Averaged across treatments, STN was greater in the 4.75- to 2.00-mm and <0.25-mm size classes than the other size classes. When pea was excluded in crop species for data analysis, STN, averaged across N rates, was greater in surface residue placement under spring wheat and fallow than residue incorporation under spring wheat in the 2.00- to 0.25-mm and <0.25-mm size classes (Fig. 4). Averaged across crop species and N rates, STN was greater in surface residue placement than residue incorporation in the 8.00- to 4.75-mm and 4.75- to 2.00-mm size classes. Averaged across residue placements and N rates, STN was greater under fallow than spring wheat in the <0.25-mm size class. When pea was included, STN was greater in surface residue placement under spring wheat or residue incorporation under fallow than residue incorporation under spring wheat in the 2.00- to 0.25-mm size class. In the <0.25-mm size class, STN was greater in surface residue placement under pea or fallow than residue incorporation under pea. Averaged across crop species, STN was greater in surface residue placement than residue incorporation in the 8.00- to 4.75-mm and <0.25-mm size classes. Averaged across residue placements, STN was greater under pea or fallow than spring wheat in the <0.25-mm size class. As with SOC, N fertilization and residue rate had no effect on STN in aggregates, but presence of residue in the fallow increased STN in the <0.25-mm size class (Table 4).

Higher rate of N fertilization and lack of plant N uptake due to the absence of crop in the fallow may have increased STN in T6. Similar to SOC, increased residue N loss (Table 2) may have translated into higher STN in macroaggregates and silt and clay fractions in T4. In contrast, greater STN in microaggregates and silt and clay fractions than macroaggregates was probably due to rapid mineralization of STN compared with SOC. Mineralization of N due to tillage and fallow can be higher than mineralization of C (Sainju et al., 2009). With or without pea inclusion in the crop species for data analysis, rapid mineralization of N may have reduced STN in residue incorporation under spring wheat in small macroaggregates, microaggregates, and silt and clay fractions. It may be possible that fresh residue incorporated into the soil may have stimulated microbial activity and N mineralization by increasing substrate availability, thereby reducing STN in aggregates (Sisti et al., 2004). As with SOC, rapid turnover of plant N into soil N due to lower C/N ratio of pea residue or higher

TABLE 3. Effects of Residue Placement and Rate, Crop Species, and N Fertilization Rate on the Proportions of Soil Aggregates and Water-Stable Aggregates

	Aggregate Proportion				Water-Stable Aggregate Proportion	
Treatment†	**8.00–4.75 mm**	**4.75–2.00 mm**	**2.00–0.25 mm**	**<0.25 mm**	**8.00–4.75 mm**	**4.75–2.00 mm**
			kg aggregate pot^{-1}			
T1	3.17	1.68	2.75	0.40	1.48	0.84
T2	2.41	1.38	3.25	0.96	1.60	0.78
T3	1.85	1.24	3.81	1.10	1.25	0.77
T4	3.68	1.83	2.36	0.13	2.36	1.08
T5	2.70	2.05	3.04	0.20	1.54	1.20
T6	2.97	1.82	3.02	0.19	1.84	1.06
T7	1.52	1.17	3.95	1.34	1.01	0.80
T8	2.27	1.24	3.38	1.11	1.12	0.72
T9	1.62	1.24	4.00	1.13	1.04	0.80
T10	2.53	1.82	3.21	0.45	1.47	1.04
T11	2.16	1.67	3.80	0.36	1.11	1.06
T12	2.02	1.75	3.86	0.38	1.14	1.14
LSD (0.05)	1.01	0.21	0.76	0.38	0.76	0.24
P	**	***	**	**	*	***
Mean	2.42B‡	1.58C	3.36A	0.65D	1.42A	0.94B
Contrast						
Residue vs. no residue in the fallow						
(T5 + T11 vs. T1)	−0.74	0.18*	0.67*	−0.11	−0.15	0.29**
Wheat residue rate (2.5 vs. 5.0 g kg^{-1})						
(T3 vs. T7)	0.33	0.07	−0.14	−0.24	0.24	−0.03

Orthogonal contrasts were used to determine the effects of residue presence (T5 + T11 vs. T1) and rate (T7 vs. T3).
*Significant at $P = 0.05$.
**Significant at $P = 0.01$.
***Significant at $P = 0.001$.
†See Table 1 for treatment description.
‡Numbers followed by different letters within a row in a set are significantly different at $P \leq 0.05$ by the least-squares means test.

soil water content under fallow may have increased STN under pea or fallow than spring wheat in microaggregates and silt and clay fractions. Increased N substrate availability due to increased residue rate also may have increased STN in microaggregates and silt and clay fractions.

Particulate Organic Carbon and Nitrogen

Particulate organic C was greater in residue incorporation under fallow with 0.96 g N pot^{-1} (T12) than residue incorporation under wheat and pea with 0.11 to 0.96 g N pot^{-1} (T9, T10, and T11) in the 4.75- to 2.00-mm size class (Table 5). In the <0.25-mm size class, POC was greater in surface residue placement under pea with 0.11 g N pot^{-1} (T4) than no residue or residue incorporation under wheat and fallow with 0.11 to 0.96 g N pot^{-1} (T1, T9, and T11). Averaged across treatments, POC was greater in the 8.00- to 4.75-mm and 2.00- to 0.25-mm size classes than the other size class. With the exclusion of pea in the crop species for data analysis, POC, averaged across crop species and N rates, was greater in the surface residue placement than residue incorporation in the <0.25-mm size class (Fig. 5). With the inclusion of pea, POC, averaged across crop species, was similarly greater in surface residue placement than residue incorporation in the <0.25-mm size class. Averaged across residue placements, POC was greater under fallow than pea in the 8.00- to 4.75-mm size class, but the trend reversed in the <0.25-mm size class. Similar to SOC, N fertilization, residue rate, and presence of residue in the fallow did not affect POC.

Residue incorporation under fallow with high N rate appeared to increase POC in T12 compared with other treatments in intermediate aggregates, reasons for which were not clear. When averaged across crop species and N rates, POC, however, was not different between residue placements in all aggregate size classes, except the <0.25-mm size class (Fig. 5). As with SOC, higher residue C loss (Table 2) may have translated into increased POC in T4 in microaggregates and silt and clay fractions. It appeared that surface residue placement increased POC compared with residue incorporation particularly in microaggregates and silt and clay fractions (Fig. 5), which are more stable than macroaggregates (Elliott, 1986; Six et al., 1998). Although pea residue with lower C/N ratio can mineralize rapidly than spring wheat residue (Kuo et al., 1997), coarse organic matter–C under pea was protected better from mineralization in microaggregates and silt and clay fractions than macroaggregates. As with SOC, inclusion of C-rich young residue may have increased POC in macroaggregates than microaggregates and silt and clay fractions.

Particulate organic N was greater in surface residue placement under pea with 0.11 g N pot^{-1} (T4) than surface residue placement under fallow with 0.11 g N pot^{-1} (T5) and residue incorporation under wheat with 0.96 g N pot^{-1} (T9) in the 8.00- to 4.75-mm size class (Table 5). In the 4.75- to 2.00-mm size class,

TABLE 4. Effects of Residue Placement and Rate, Crop Species, and N Fertilization Rate on SOC and STN in Aggregates

Treatment†	SOC in Aggregates				STN in Aggregates			
	8.00–4.75 mm	4.75–2.00 mm	2.00–0.25 mm	<0.25 mm	8.00–4.75 mm	4.75–2.00 mm	2.00–0.25 mm	<0.25 mm
	g C pot^{-1}				g N pot^{-1}			
T1	98.3	98.5	96.9	97.2	10.1	10.7	10.3	10.5
T2	103.3	102.4	100.3	99.8	10.9	11.0	10.7	11.3
T3	102.5	102.2	99.1	99.8	10.8	11.1	10.5	11.4
T4	102.5	101.7	99.5	108.4	10.9	10.8	10.4	12.6
T5	101.8	102.1	97.7	103.6	10.4	10.5	10.2	11.8
T6	102.2	101.4	96.9	94.6	11.1	11.1	10.2	11.0
T7	104.8	105.2	98.8	101.2	10.7	11.7	10.3	11.4
T8	98.9	98.9	99.0	98.7	10.3	10.7	9.9	10.6
T9	98.3	101.1	97.9	94.6	10.4	11.1	10.5	10.7
T10	99.8	100.0	99.3	101.1	10.3	11.1	10.3	11.3
T11	101.5	98.7	99.8	99.2	10.3	10.9	10.6	11.6
T12	100.1	100.7	99.0	100.3	10.6	11.0	10.3	11.5
LSD (0.05)	NS	4.0	NS	6.6	0.8	NS	NS	0.7
P	NS	*	NS	*	*	NS	NS	**
Mean	101.3A‡	101.1A	98.7B	99.7B	10.6B	11.0A	10.3C	11.2A
Contrast								
Residue vs. no residue in the fallow								
(T5 + T11 vs. T1)	3.4	1.9	1.8	4.2	0.24	−0.04	0.14	1.20**
Wheat residue rate (2.5 vs. 5.0 g kg^{-1})								
(T3 vs. T7)	−2.3	−3.0	0.2	−1.4	−0.10	−0.54	0.29	−0.02

Orthogonal contrasts were used to determine the effects of residue presence (T5 + T11 vs. T1) and rate (T7 vs. T3).
*Significant at $P = 0.05$.
**Significant at $P = 0.01$.
†See Table 1 for treatment description.
‡Numbers followed by different letters within a row in a set are significantly different at $P \leq 0.05$ by the least-squares means test.
NS: not significant; POC: particulate organic C; PON, particulate organic N.

PON was greater in residue incorporation under fallow with 0.96 g N pot^{-1} (T12) than surface placement or incorporation of residue under wheat and pea with 0.11 to 0.96 g N pot^{-1} (T4, T6, T7, and T9). In the 2.00- to 4.75-mm size class, PON was greater in surface residue placement under wheat with 0.11 g N pot^{-1} (T2) than surface placement or incorporation of residue under wheat and fallow with 0.96 g N pot^{-1} (T6, T7, and T12). In the <0.25-mm size class, PON was greater in surface residue placement under pea with 0.11 g N pot^{-1} (T4) than no residue or surface placement and incorporation of residue under wheat and fallow with 0.11 to 0.96 g N pot^{-1} (T1, T7, T8, T9, and T10). Averaged across treatments, PON was greater in the 8.00- to 4.75-mm size class than the other size classes. Presence of residue in the fallow increased PON in the <0.25-mm size class. When pea was not included in crop species, PON, averaged across N rates, was greater in surface residue placement than residue incorporation under spring wheat in the 2.00- to 0.25-mm and <0.25-mm size classes (Fig. 6). Averaged across crop species and N rates, PON was greater in residue incorporation than surface residue placement in the 4.75- to 2.00-mm size class, but the trend reversed in the 2.00- to 0.25-mm and <0.25-mm size classes. When pea was included, PON was greater in surface residue placement under spring wheat than the other treatments, except residue incorporation under fallow, in the 2.00- to 0.25-mm size class. In the <0.25-mm size class, PON was greater in surface residue placement under pea than residue incorporation under spring wheat and pea. Averaged across crop species, PON was greater in residue incorporation than surface residue placement in the 4.75- to 2.00-mm size class, with reversed trends in the 2.00- to 0.25-mm and <0.25-mm size classes. Averaged across residue placements, PON was greater under spring wheat than pea in the 4.75- to 2.00- and 2.00- to 0.25-mm size classes. Nitrogen fertilization and residue rates had no effect on PON.

Nitrogen in coarse organic matter fraction varied with treatments in various aggregate size classes, but surface residue placement under wheat and pea increased PON in most aggregate size classes. As with STN, increased residue N loss in surface residue placement under pea (Table 2) appeared to translate increased PON in T4 in large macroaggregates, microaggregates, and silt and clay fractions. It could be possible that residue N rather than residue C was turned over rapidly to coarse organic matter–N, thereby increasing PON in large macroaggregates, microaggregates, and silt and clay fractions, a case similar to that observed for STN vs. SOC. This was also supported by greater PON in large macroaggregates where N-rich young residue may have converted mostly to PON than other aggregates. Unlike other soil C and N fractions, PON clearly appeared to increase in surface residue application under spring wheat in small macroaggregates, microaggregates, and silt and clay fractions. It is likely that coarse organic matter–N was protected from mineralization better for spring wheat residue than for pea residue in

TABLE 5. Effects of Residue Placement and Rate, Crop Species, and N Fertilization Rate on Soil POC and PON in Aggregates

	POC in Aggregates				PON in Aggregates			
Treatment†	**8.00–4.75 mm**	**4.75–2.00 mm**	**2.00–0.25 mm**	**<0.25 mm**	**8.00–4.75 mm**	**4.75–2.00 mm**	**2.00–0.25 mm**	**<0.25 mm**
	g C pot^{-1}				g N pot^{-1}			
T1	22.7	18.2	24.2	16.8	1.77	1.43	2.01	1.13
T2	25.2	20.8	28.1	20.2	2.00	1.77	2.51	2.22
T3	24.7	19.7	25.6	20.5	1.75	1.27	1.59	1.73
T4	23.5	18.7	23.8	23.5	2.23	0.74	1.57	2.35
T5	25.2	20.3	23.1	17.0	1.61	1.21	1.55	1.86
T6	25.8	20.5	23.1	21.1	1.97	1.01	1.06	1.59
T7	24.2	20.8	23.7	20.9	2.12	1.09	0.97	1.24
T8	25.3	20.2	24.3	18.0	1.96	1.97	1.23	1.22
T9	20.1	17.6	22.4	14.6	0.87	1.03	1.34	0.82
T10	22.9	17.9	24.6	17.9	1.77	1.54	1.24	1.21
T11	27.6	17.3	24.0	14.0	2.19	1.46	1.88	1.80
T12	24.3	26.0	23.5	22.4	1.81	2.00	0.91	1.57
LSD (0.05)	NS	8.0	NS	6.5	0.61	0.90	1.31	0.89
P	NS	*	NS	*	*	*	*	**
Mean	24.4A‡	19.9B	24.2A	19.0B	1.86A	1.38B	1.47B	1.54B
Contrast								
Residue vs. no residue in the fallow								
(T5 + T11 vs. T1)	3.7	0.6	−0.7	−1.3	0.13	−0.10	−0.30	0.70*
Wheat residue rate (2.5 vs. 5.0 g kg^{-1})								
(T3 vs. T7)	0.5	−1.1	2.0	−0.4	−0.36	0.17	0.62	0.49

Orthogonal contrasts were used to determine the effects of residue presence (T5 + T11 vs. T1) and rate (T7 vs. T3).
*Significant at $P = 0.05$.
**Significant at $P = 0.01$.
†See Table 1 for treatment description.
‡Numbers followed by different letters within a row in a set are significantly different at $P \leq 0.05$ by the least-squares means test.
NS: not significant; POC: particulate organic C; PON, particulate organic N.

small aggregates, probably due to higher C/N ratio. Residue incorporation, however, increased PON in intermediate macroaggregates, reasons for which were not known.

CONCLUSIONS

Soil aggregation and associated C and N levels changed significantly with management practices during a crop-growing season under controlled soil and environmental conditions in the greenhouse. Changes were mostly associated with the type, amount, and placement of residue in the soil when increased C and N losses from the surface placement of pea residue translated into greater proportions of large water-stable and unstable macroaggregates and higher soil C and N levels in microaggregate and silt and clay fractions. Increased residue rate increased C storage in intermediate macroaggregates and surface placement of residue under pea or fallow increased soil aggregation and C and N storage in small macroaggregates. Presence of residue in the fallow increased N storage in microaggregates and silt and clay fractions, but N fertilization rate had no effect on soil aggregation and C and N fractions. Surface application of the residue in a no-till simulation increased soil aggregation and C and N storage compared with residue incorporation, and effects were more pronounced under pea and fallow than spring wheat during a crop-growing season when soil and climatic conditions were controlled in the greenhouse. These results agreed with those observed for long-term experiment in the field.

ACKNOWLEDGMENTS

The authors appreciate the excellent support of Joy Barsotti and Thecan Caesar-TonThat for analyzing soil and plant samples in the laboratory.

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